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Keith G. Condie
Joy L. Rempe
Darrell Knudson
Kune Y. Suh
Fan-Bill Cheung
Sang-Baik Kim

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Keith G. Condie, Joy L. Rempe, and Darrell Knudson
INEEL
P.O. Box 1625, MS 3840
Idaho Falls, ID 83415-3840
Tel: 208-526-9383 , Fax:208-526-2930 , Email: kgc@inel.gov

Kune Y. Suh
Seoul National University
Department of Nuclear Engineering
San 56-1, Silliim-Don, Kwanak-Gu, Seoul, Korea
Tel: 82-2-880-8324, Fax: 82-2-889-2688, Email: kysuh@snu.ac.kr

Fan-Bill Cheung
The Pennsylvania State University
Department of Mechanical & Nuclear Engineering
304 Reber Building University Park, PA 16802
Tel: 814-863-4261, Fax: 814-863-8682; Email: fxc4@psu.edu

Sang-Baik Kim
Korea Atomic Energy Research Institute
Severe Accident Research Project
P.O. Box 105, Yuseoung, Taejon, Korea, 305-600
Tel: 82-42-868-8368, Fax: 82-42-861-2574; E-mail: sbkim2@kaeri.re.kr

Abstract – *An enhanced in-vessel core catcher is being designed and evaluated as part of a joint United States (U.S.) - Korean International Nuclear Engineering Research Initiative (INERI) investigating methods to insure In-Vessel Retention (IVR) of core materials that may relocate under severe accident conditions in advanced reactors. To reduce cost and simplify manufacture and installation, this new core catcher design consists of several interlocking sections that are machined to fit together when inserted into the lower head. If needed, the core catcher can be manufactured with holes to accommodate lower head penetrations. Each section of the core catcher consists of two material layers with an option to add a third layer (if deemed necessary): a base material, which has the capability to support and contain the mass of core materials that may relocate during a severe accident; an oxide coating material on top of the base material, which resists interactions with high-temperature core materials; and an optional coating on the bottom side of the base material to prevent any potential oxidation of the base material during the lifetime of the reactor. This paper summarizes the status of core catcher design and evaluation efforts, including analyses, materials interaction tests, and prototypic testing efforts.*

I. INTRODUCTION

If there were inadequate cooling during a reactor accident, a significant amount of core material could become molten and relocate to the lower head of the reactor vessel, as happened in the Three Mile Island Unit 2 (TMI-2) accident. If it is possible to ensure that the vessel head remains intact so that relocated core materials are retained within the vessel, the enhanced safety associated with these plants can reduce concerns about containment failure and associated risk. For example, the enhanced safety of the Westinghouse Advanced 600 MWe PWR (AP600), which relied upon External Reactor Vessel Cooling (ERVC) for In-vessel Retention (IVR), resulted in the U.S. Nuclear Regulatory Commission (US NRC) approving the design without requiring certain conventional features common to existing LWRs. Consequently, IVR of core melt is a key severe accident management strategy adopted by some operating nuclear power plants and proposed for some advanced light water reactors (ALWRs). However, it is not clear that currently proposed ERVC without additional enhancements could provide sufficient heat removal for higher-power reactors (up to 1500 MWe).

I.A. Project Objective

A U.S. - Korean INERI project has been initiated in which the Idaho National Engineering and Environmental Laboratory (INEEL), Seoul National University (SNU), Pennsylvania State University (PSU), and the Korea Atomic Energy Research Institute (KAERI) will investigate the performance of ERVC and core catchers to determine if IVR is feasible for reactors up to 1500 MWe. This program is initially focusing on the Korean Advanced Power Reactor 1400 MWe (APR1400) design. However, improved margins relative to IVR offered by each modification will be evaluated such that methods can easily be applied to a wide range of existing and advanced reactor designs.

A major effort in this collaborative, three-year, INERI project is to develop an in-vessel core catcher design for the APR1400 and to provide initial data to demonstrate that this core catcher design will enhance in-vessel debris coolability. This paper summarizes the status of core catcher design and evaluation efforts, including analyses, materials interaction tests, and prototypic testing efforts.

I.B. Design Approach

The approach adopted in this INERI for developing a conceptual APR1400 core catcher design is illustrated in Figure 1. This design relies on several mechanisms to enhance IVR, such as retention and dilution of the decay heat in the relocated core materials and heat transfer through the lower surface of the core catcher via narrow gap cooling.

As suggested in the figure, the conceptual design was developed to meet design criteria that considered previous core catcher designs and approaches. As discussed in Reference 1, these criteria encompassed a wide range of considerations, including possible heat and structural loads, materials interactions, impact on reactor performance or coolant circulation, reactor lifetime,[1] installation and maintenance, and cost. A conceptual design was developed and assessed using a combination of scoping materials analyses, scoping flow analyses, scoping thermal analyses, scoping structural analyses, and scoping materials interaction tests. To demonstrate the viability of this design, more detailed calculations will be performed using SCDAP/RELAP5-3D©,[2] and results will be evaluated to assure that the core catcher can withstand estimated loads from materials that may relocate during a severe accident. In addition, more detailed data will be obtained in two areas. First, data are needed to estimate the heat that can be removed from the narrow "engineered" gap between the in-vessel core catcher and the inner surface of the reactor vessel lower head. These data are being obtained from the Gap-cooling Apparatus against Molten Material Attack (GAMMA) facilities at SNU and the Critical Heat Flux in Gap (CHFG) facility at KAERI to formulate a complete "narrow gap" boiling curve. Second, data are needed to understand the heat loads to the core catcher and demonstrate the viability of materials proposed for the in-vessel core catcher. As illustrated in the figure, these needs will be addressed by conducting tests in several facilities: the Simulation of Internal Gravity-driven Melt Accumulation (SIGMA) facilities at SNU will be used to develop natural convection heat transfer correlations and the Lower-plenum Arrested Vessel Attack - Gap (LAVA)-GAP facility at KAERI and INEEL's high temperature test laboratory (HTTL) will be used to assess the potential for interactions with prototypic materials that may relocate during a severe accident.

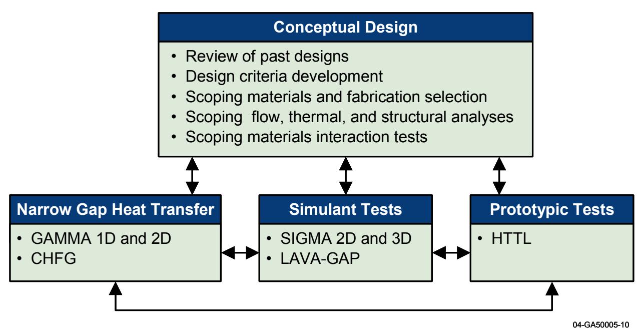

Figure 1. Activities to develop a core catcher.

Detailed information about the design and capabilities of these experimental facilities can be found in several references (e.g., Reference 1). The remainder of this paper is devoted to describing results from core catcher development efforts completed during the second year of this project. However, it should be noted that the core catcher design process is iterative. As data are obtained from various experimental facilities, it is anticipated that the preliminary core catcher design may be modified. Likewise, experimental test plans are impacted by results from other activities Furthermore, only preliminary core catcher design and evaluations will be completed in this INERI. If feasibility studies demonstrate that the proposed core catcher design and materials are viable and enhance the potential for IVR, more detailed studies and testing will

[1] The APR1400 is designed for a 60-year lifetime.

be needed before this concept is implemented in a reactor design. Such testing would confirm the long-term endurance of the proposed materials to hydrodynamic loads during operating and accident conditions. In addition, confirmatory testing of irradiation and coolant chemistry effects on coating performance may be warranted.

II. CORE CATCHER DESIGN

A preliminary design was developed that builds upon an in-vessel core catcher concept proposed by Hwang and Suh.[3] However, the new core catcher design consists of several interlocking sections (see Figure 2). The use of multiple sections reduces cost, and simplifies manufacture and installation. The sections are machined such that they fit together when inserted into the lower head. For reactor designs with penetrations, such as the APR1400, the core catcher is manufactured with holes to accommodate lower head penetrations. Each section of the core catcher (see Figure 2) consists of two material layers with an option to add a third layer (if deemed necessary): a base material, which has the capability to support and contain the mass of core materials that may relocate during a severe accident; an oxide coating material on top of the base material, which resists interactions with high-temperature core materials; and an optional coating on the bottom side of the base material to prevent any potential oxidation of the base material during the lifetime of the reactor.

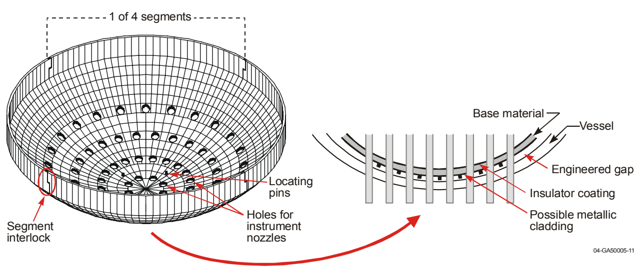

Figure 2. APR1400 core catcher conceptual design.

II.A. Fabrication

Various types of application methods, such as chemical vapor deposition, plasma spraying, and painting, were reviewed; and preliminary evaluation suggests that the insulator coating should be applied via a plasma spray process. The plasma spray process, which is relatively inexpensive, can provide a chemically stable, dense, rugged, and bonded coating of materials for any desired thickness.

To optimize the performance of the plasma spray coating, several options are available, such as substrate surface preparation, plasma spray coating parameter optimization, and the inclusion of a "bond" coating between the substrate and the ceramic overlayer. INEEL investigated all three of these options.

II.B. Preliminary Materials Evaluation

During the first year of this project, scoping materials evaluations identified candidate substrate and coating materials for the core catcher. Materials selection considered thermal, structural, and nuclear properties.

Stainless steel 304 and carbon steel SA533 are candidate base materials. Thermal and structural properties for these materials are similar.[4] Although carbon steel is less expensive than stainless steel, the use of stainless steel avoids the need to add a corrosion-resistant undercoating on the core catcher.

From a wide spectrum of oxide materials, cerium dioxide, magnesium oxide, and zirconium dioxide were identified as promising candidates for the core catcher upper surface coating. All three materials have relatively high melting points and low thermal conductivities.[2,5] The coating materials were also evaluated for their ability to resist cracking (and protect the base material) using a parameter suggested by Winkelmann and Schott.[6]

In addition, the potential for interactions between the core catcher and relocated corium materials was evaluated using phase diagram information.[7] Although initial evaluations suggested that MgO material properties were superior, the cost for ZrO_2 powder is considerably less. In addition, there is considerably more experience with applying yttria-stabilized ZrO_2 using plasma spray techniques. Hence, it was decided to evaluate both coatings (As discussed in Section II.C, scoping analyses suggest that CeO_2 performance was less desirable as a coating). However, difficulties in spraying high purity MgO limited evaluations to considering the performance of coatings that contained MgO. Specifically, MgO-containing coatings could only be evaluated that were prepared from mixed MgO/Al_2O_3 powders and compounds of magnesium aluminate and magnesium zirconate.

As discussed above, the use of bond coatings has been found to improve the performance of thermal spray coatings. INEEL investigated three bond coating materials: 100% nickel, a 95% nickel / 5% aluminum alloy, and Inconel 718. References 8 through 10 indicate that these materials have similar melting temperatures (1610-1730 K), but much higher thermal conductivities than proposed substrate materials. However, information in Reference 10 suggests that the inclusion of aluminum in the bond coating could lead to reactions with iron and coating materials at relatively low temperatures.

The coefficient of thermal expansion is an important consideration in evaluating if the coatings and substrate are compatible. Figure 3 compares thermal expansion coefficients of candidate coating, base, and substrate materials.[4, 11] Results in the figure indicate that magnesium oxide may be a good choice for a coating material because its expansion and contraction are most closely aligned with the expansion and contraction of proposed base materials. Curves in Figure 3 also suggest that the nickel bond coating material may reduce differences between expansion of proposed oxide coating and substrate materials.

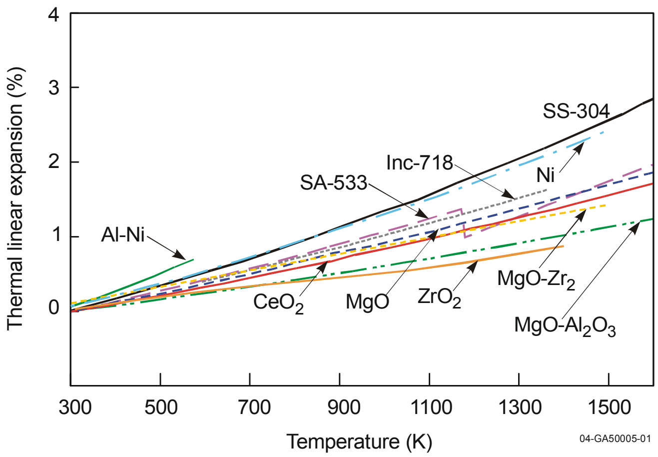

Figure 3. Insulator, bond, and base material thermal expansion coefficients.

II.C. Scoping Analysis

Scoping analyses and materials interaction tests were performed to gain additional insights about core catcher design and viability. Results from these analyses are summarized below. More detailed information about these calculations can be found in Rempe, et al.[12]

Simple thermal analyses were performed using the SCDAP/RELAP5-3D© code to gain insights about the thickness and materials that should be selected for the base and coating of the core catcher. A range of conditions were investigated that reflect the anticipated conditions to which the core catcher might be subjected. Upper and lower values for parameters were selected based on the estimated space available within the lower plenum for the core catcher, and methods available for fabricating a core catcher as well as the estimated heat transfer from relocated debris and narrow gap cooling. Figure 4 shows the simple RELAP hydrodynamic model used for simulating the thermal response of the core catcher. As shown in the figure, a single RELAP volume was used to represent the hydrodynamic conditions of fluid entering the vessel (Volume 500) and a single volume was used to represent the fluid in the reactor vessel (Volume 598). These two volumes are connected by a junction. Note that fluid and vapor may travel to and from the reactor vessel volume, depending on conditions in the vessel.

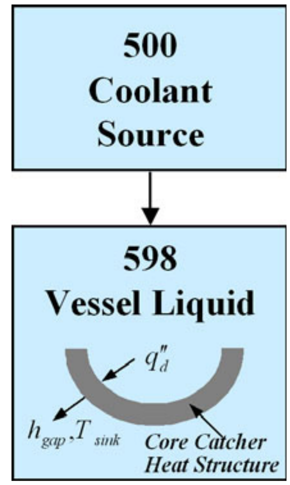

Figure 4. RELAP hydrodynamic model.

Results from scoping SCDAP/RELAP5-3D© calculations indicate that the thermal performance of insulator coatings are affected primarily by their thermal conductivity and melting temperature. Hence, cerium dioxide is less desirable because its melting temperature is approximately 400 ºC lower than other oxide materials evaluated. Results also indicate that the core catcher thermal performance is not significantly impacted by the type of steel (SS304 or SA533B1) selected for the base material, the thickness of the base or coating material, or the porosity of the coating material.

A structural assessment was completed to determine an appropriate core catcher thickness to support the mass of materials that may relocate during a severe accident. Although a linked structural / thermal analysis would provide a more detailed basis for selecting the core catcher thickness, an initial estimate for the required core catcher thickness was obtained from a simple structural analysis that assumed relocated masses were bounded by SCDAP/RELAP5-3D© APR1400 results reported in Knudson, et al.[13] As shown in Figure 5, the assumed relocated materials approximately fill a core catcher with a thickness, $t_{catcher}$. The maximum load to the core catcher was calculated by estimating the load to a central portion of the core catcher with radius, r_{cyl}, assuming that the core materials were molten and level within the core catcher. Results suggest that the core catcher's base material should be at least 2 cm thick to support the loads associated with relocated materials during a severe accident (and smaller thicknesses may be possible, depending upon heat removal capabilities associated with narrow gap cooling).

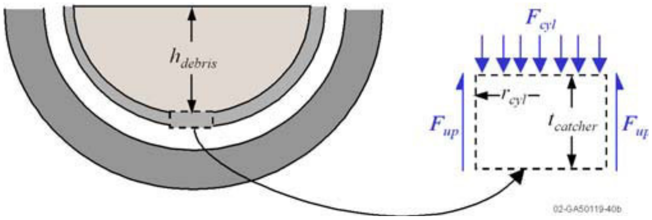

Figure 5. Geometry assumed to estimate forces on a central cylinder of the core catcher.

It is envisioned that the core catcher would be placed just above the inner surface of the reactor vessel (creating a vessel-to-core catcher gap of approximately 0.5 cm). To alleviate concerns about the impact of a core catcher on coolant flow in the reactor, a simple analysis was performed to demonstrate that the mass flow diverted by the core catcher is minimal. Using the geometry shown in Figure 6, a relationship was developed for estimating the ratio of the mass flowrate under the core catcher, $\dot{m}_{cc}$, to the mass flowrate through the downcomer, $\dot{m}_{DC}$. Results indicate that only 2% of the RCS flow from the downcomer may be diverted beneath the core catcher if it is placed approximately 0.5 cm above the reactor vessel inner surface. Hence, initial investigations suggest that the impact of the core catcher on RCS flow is negligible. However, confirmatory testing is needed to verify the long-term endurance of the core catcher design to hydrodynamic loads during operating and accident conditions.

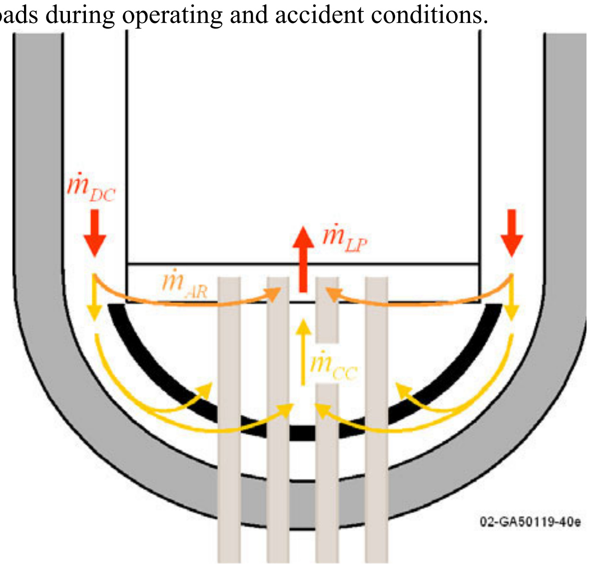

Figure 6. Geometry assumed for flow analysis.

In summary, results from scoping thermal and structural analyses suggest that an in-vessel core catcher is feasible. In addition to gaining insights about the thickness and materials for each layer of the core catcher, analyses showed that the impact of the core catcher on coolant flow in the reactor vessel is minimal. As discussed below, additional insights about the core catcher design were also obtained from materials interaction tests.

II.D. Materials Interaction Tests

As part of the investigation to select an appropriate core catcher coating, high temperature tests were conducted to determine if materials interactions occur at temperatures lower than the melting temperature of core catcher base and coating materials. In addition, sensitivity studies were performed to optimize thermal spray parameters for coating materials.

Figure 7 contains photos of uncoated and coated samples. Samples were machined from 1inch stainless steel (SS 304) rod. Each sample was approximately 2 inches long.

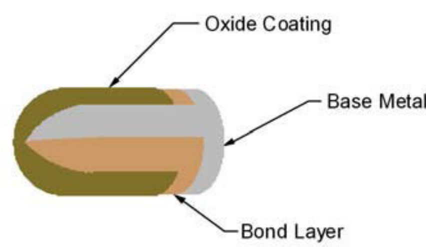

Figure 7. Samples with and without spray coating and diagram illustrating spray coating layers.

Figure 8 illustrates the configuration used to heat samples in a tube furnace. Although this horizontal tube furnace is rated at 1700 ºC, the furnace temperature was set to 1400 ºC during these tests (because this temperature is just below the stainless steel melting point). This temperature was checked (and found to be accurate) with a two-color optical pyrometer. As shown in Figure 8, a steam or argon environment was obtained by flowing the vapor or gas through one end of the tube furnace for a period of 30 minutes prior to testing. At the end of the planned test period (a 5 minute warm-up at the furnace entrance followed by 10 minutes at full temperature), the flow is stopped, and the specimen is slowly removed from the furnace. Samples were individually tested to avoid unwanted interactions between oxides.

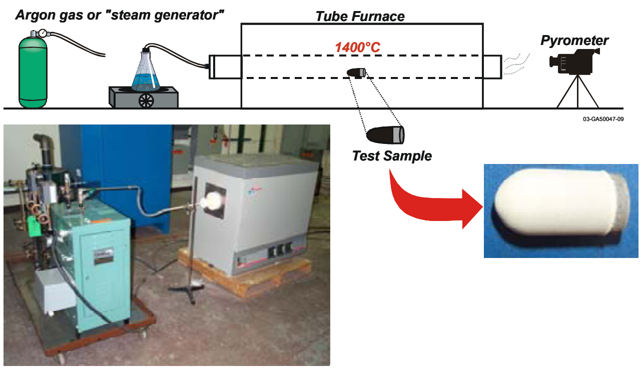

Figure 8. Diagram and photo illustrating setup for materials tested in steam.

Samples were prepared for conducting the tests listed in Table 1. As discussed above, several types of ceramic coatings were considered. Because ZrO_2 coatings are less expensive and widely used, initial investigations considered this ceramic material. Then, samples with coatings containing MgO were prepared with the bond coating/coating thickness combinations deemed to yield the optimum performance. Detailed information about results from other tests may be found in Rempe, et al.[14] Results from selected tests are summarized below.

Table 1. Coating parameter sensitivities

Parameter	Range
Coating thickness	200, 500, and 1000 µm
Bond coating	100 µm thick Ni, Ni-Al, or Inconel-718 bond coating (or no bond coating)
Oxide material	zirconium dioxide magnesium oxide[a] magnesium zirconate magnesium aluminate (spinel)

a. As noted above, Al_2O_3 powder was "mixed" with the magnesium oxide in order to obtain a thermal spray coating.

Figure 9 compares endstates from samples tested in steam to investigate the impact of coating thickness. As evidenced by the gray oxide material on the outer surface of all three samples in this figure, materials interactions and substrate oxidation occurred irrespective of coating thickness. However, coating thickness significantly affects the amount and type of degradation. Comparisons of the endstates shown in Figure 9 suggest that coatings thinner than 500 µm allowed oxygen to penetrate to the underlying steel and degrade the sample's outer surface. There was a tendency for coatings to remain intact as thickness was increased. However, some cracking and flaking occurred during cooldown of samples with thicker coatings. In steam tests, the 200 µm coated sample became perforated with large holes. As shown in Figure 9, gray material is present on the outer surface of samples with thicker coatings that were tested in steam. However, this material appears to have "flowed" from uncoated regions of the samples along the intact outer surface of the coatings (see flow patterns in Figure 9). Hence, results suggest that coatings should be at least 500 µm thick.

200 µm

500 µm

1,000 µm

Figure 9. Impact of coating thickness

Endstates from samples with coatings that performed the best are shown in Figure 10. As shown in this figure, the sample coated with zirconium dioxide over a 100 µm Inconel 718 bond coating experienced no materials interactions or cracking. The sample coated with magnesium zirconate also performed well. Although it experienced no materials interactions, cracking was evident during cooldown. INEEL experience with thermal coatings suggests that the zirconium dioxide coating with the Inconel 718 bond coating will perform better at the high temperature, oxidizing conditions expected during a severe accident.[15] Hence, initial prototypic tests will use this coating. As discussed below, these high temperature prototypic tests are being conducted at INEEL's High Temperature Test Laboratory (HTTL).

100 µm Inconel 718 beneath 500 µm zirconium dioxide

500 µm magnesium zirconate

Figure 10. Bond coating / oxide material combinations with superior performance

III. PROTOTYPIC TESTING

As noted above, the objective of the prototypic tests is to verify that candidate core catcher materials will not interact with high-temperature materials expected to relocate during a severe accident. The test assembly and heater designs that will be used for these prototypic tests are described below. Note that these designs have been developed so that they can easily interface with existing INEEL HTTL equipment. Efforts to verify the performance of these designs are also reported.

III.A. Facility Design

Figure 11 illustrates the design of the test assembly. The carbon steel crucible and stainless steel cover were developed for previous tests at INEEL. As shown in Figure 12, the crucible stands within a stainless steel enclosure ideally suited for high temperature testing with radioactive materials. Within the carbon steel crucible are placed high temperature, insulating materials, such as the RS-100 insulation board, the ZYFB-3 insulation board, and graphite. The simulated core catcher or "trough" is fabricated by machining out a curved region in a rectangular metal block. As discussed above, the simulated core catcher will consist of a stainless steel (SS 304) base material on which thermal plasma spraying techniques are used to apply a 100 μm bond coat of Inconel 718 beneath a 500 μm thick coating of ZrO_2.

Approximately 1.3 kg of corium material is placed in the core catcher and heated using a resistance heater that is connected to the existing power supply in CFA 622. Tests are conducted using a corium material with a composition similar to that of material that relocated during the Three Mile Island Unit 2 (TMI-2) accident. Specifically, the corium will be approximately 80% uranium dioxide and 20% zirconium dioxide.

III.B. Heater Design

Based on INEEL experience with developing and testing various types of heaters, a unique resistance heater design is proposed for these tests. This resistance heater is composed of rhenium wires that are laser-welded together to obtain a varying diameter profile that increases away from the center as shown in this figure. After the rhenium wires are laser-welded together, a 0.020 inch thick hafnia coating is applied via air plasma spraying. Molybdenum leads (0.25 inch diameter) are attached to each end of the resistance heater (via laser welding) after the hafnia coating is applied.

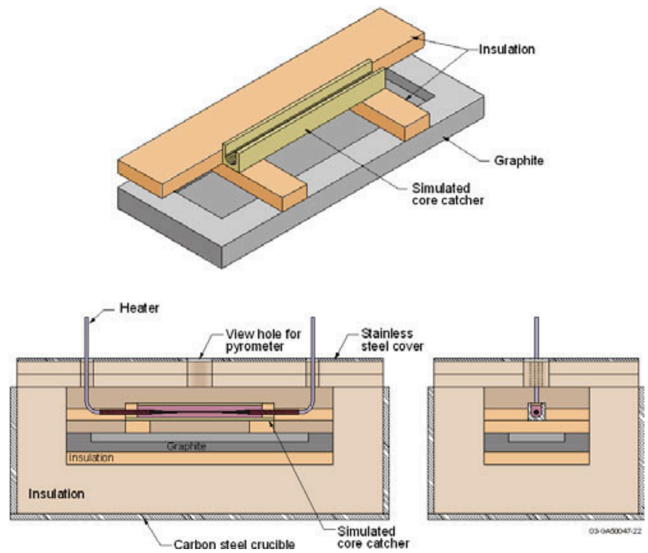

Figure 11. Assembly for prototypic testing.

Figure 12. Carbon steel crucible in stainless steel enclosure.

Materials for the resistance heater were selected based on their thermal and electrical properties.[16,17] Rhenium was selected for the electrode because of its high melting point (3450 K), its ductility, and its low electrical resistivity. Hafnia was selected because of its high electrical resistivity and its high melting point (3085 K). As shown in Figure 13, the use of these two materials for the electrode and insulator coating is particularly attractive because they have similar coefficients of thermal expansion over a wide range of temperatures (which prevents the hafnia from cracking when the electrode reaches high temperatures). Less expensive molybdenum was selected for the leads because it has a relatively high melting temperature (2898 K) and its lower resistivity and cost (relative to rhenium).

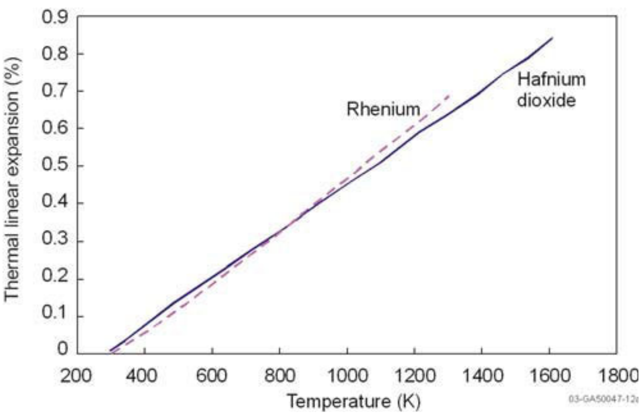

Figure 13. Thermal coefficients of expansion for hafnia and rhenium.

Figure 14 compares the electrical resistivity of hafnia and rhenium. As shown in this figure, the electrical resistivity of hafnia drops exponentially with increasing temperature. At 3200 K, the electrical resistivity is only six orders of magnitude greater than the resistivity of the rhenium electrode. This small difference in electrical resistivity between the hafnia insulator and the rhenium electrode allows current to flow through the hafnia as well as the rhenium. The net result is a reduction in the total resistance of the heater and the development of a non-uniform axial voltage gradient in the electrode. The joule-heating rate in the electrode is then no longer uniform, resulting in large axial temperature gradients in the rhenium electrode. To overcome this difficulty, a combined electrical / thermal analysis was performed to iteratively develop an electrode shape that produces a near-constant axial temperature profile at a power level and at temperatures sufficient to melt the corium. Using corium thermal properties,[2] calculations predict that approximately 1.5×10^6 J of heat are required to melt the entire 1.3 kg of corium contained in a perfectly insulated core catcher (this mass neglects any corium displacement by the resistance heater). Although it is recognized that additional heat must be delivered to the test facility to compensate for heat losses to the surrounding test assembly structures, this amount of heat provides a lower bound for the amount of heat that must be produced by the resistance heater for these tests.

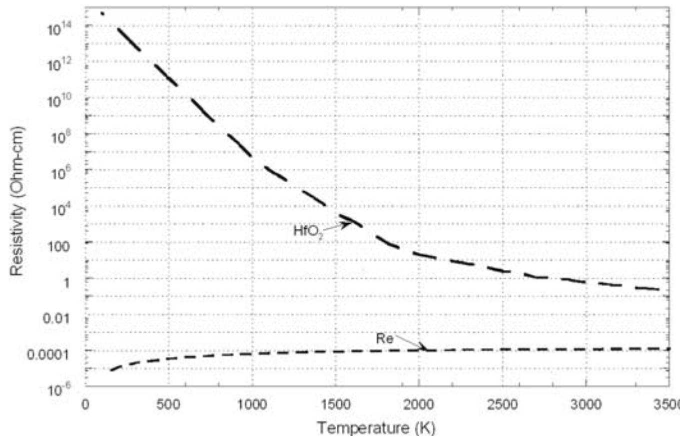

Figure 14. Electrical resistivity of hafnia compared to rhenium as a function of temperature.

III.C. Heater Performance Tests

Prior to conducting any tests with prototypic materials, several tests were conducted to verify the performance of the proposed heater design. The configuration employed for the resistance heater performance verification test is shown in Figure 15. The test assembly consists of a quartz tube mounted in a horizontal position with lab stands at each end. End plugs for the quartz tube consist of high-temperature insulation material. Holes in the end plugs accommodate heater leads, the stainless steel entrance tube for the argon cover gas, and argon gas exit flow holes.

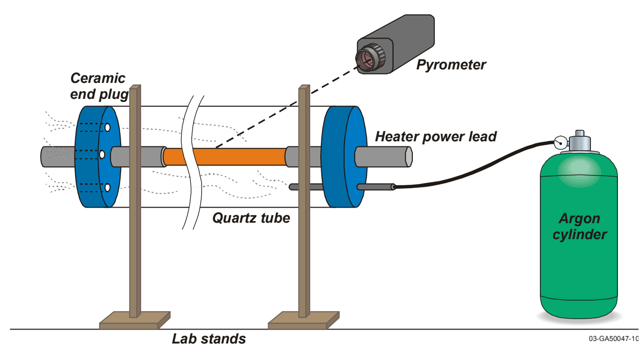

Figure 15. Schematic illustrating heater demonstration test setup (not to scale).

Prior to heater performance tests, the system is purged with argon gas for 30 minutes. A DC power source is then connected to the heater leads, and the current to the heater is increased in 5 amp increments. After each increment in current, the heater temperature is allowed to stabilize, and the optical pyrometer is used to measure the heater surface temperature. Increments in the current to the heater are continued until the heater has generated more than 1.5×10^6 J and until a peak heater surface temperature of approximately 2800 K (2527 ºC) is attained.

The setup for the heater performance tests is advantageous because it allows the temperature profile of the heater to be viewed and measured during heatup. Several aspects of the heater's performance when submerged in flowing argon gas versus its performance when submerged in corium materials should be noted. First, radiation and convective heat losses in this configuration are greater than heat losses expected in the prototypic tests. Hence, the surface temperature of the heater is higher in the prototypic tests. Second, there is the potential to continue the test after heater failure in the prototypic tests. The resistivity of corium material decreases at temperatures above melting to values where it is possible for the fractured rhenium heater to heat the corium by direct electrical heating.

Figure 16 shows the heater during various stages of the Trial 2 heater performance test, and the power and energy produced by the Trial 2 heater is plotted in Figure 17. As indicated in Figure 16, the heater temperature distribution became fairly uniform after the initial heatup. Data in Figure 17 show that the Trial 2 heater produced the required 1.5 x 10^6 J of energy by 15:12 (or 5000 seconds after the start of the Trial 2 test). Optical pyrometer measurements indicate that the last increase in current led to a temperature of 2540 ºC, which was above the desired peak temperature of 2527 ºC.

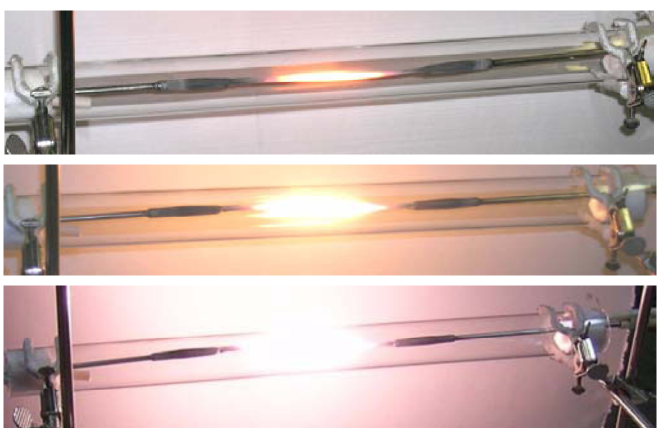

Figure 16. Progression of heatup during Trial 2 heater performance test.

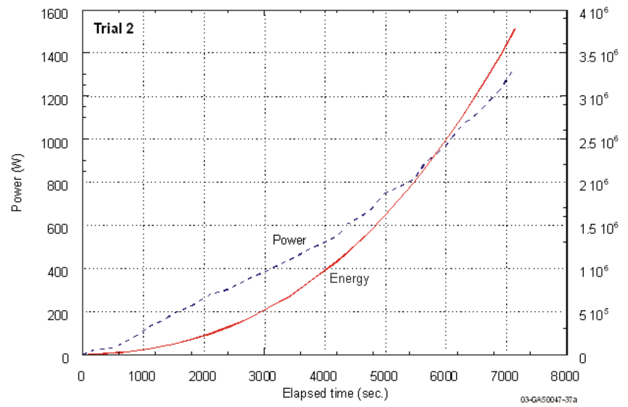

Figure 17. Power and energy produced by Trial 2 heater.

In summary, the Trial 2 test suggests that this heater design could produce the required temperatures and deliver the required heat to the corium for the proposed core catcher simulator tests. Measured heater surface temperatures exceeded 2400 ºC for over 15 minutes and 2500 ºC for over 6 minutes.

III.D. Prototypic Testing Status

As discussed above, several tests will be conducted to verify the performance of core catcher materials when they are exposed high temperature materials that may relocate during a severe accident. The primary objective for these tests is to assess what, if any, reactions will occur when candidate core catcher materials are exposed to a range of compositions of high temperature, molten prototypic materials. It is anticipated that additional modifications to proposed core catcher materials will be suggested based on initial prototypic material tests. Hence, additional tests may be conducted on modified core catcher configurations.

Prior to performing any tests in the prototypic test facility, the performance of the resistance heater and the test assembly were first verified with shakedown or checkout tests in which non-radioactive, 100% ZrO_2 was used as the corium material. Note that an uncoated, simulated core catcher was used for these checkout tests. A close-up of the simulated core catcher loaded with ZrO_2 is shown in Figure 18. As in the heater verification test, a test procedure was used in which the power to the heater was increased by increases in current and voltage.

Figure 18. Close-up of simulated core catcher loaded with heater and zirconia.

Figure 19 shows the Checkout Test 2 assembly initially after testing. As shown in this figure, the simulated core catcher, which did not have a thermal spray coating, reached temperatures that caused it to glow. It should be noted that thermocouple test data suggest that the heater was producing uniform temperatures along its length prior to its failure. Post-test examinations indicate that the heater reached temperatures sufficient to melt the ZrO_2. Furthermore, exams suggest that the heater temperatures were uniform during the test (because previously molten ZrO_2 was attached to all portions of the heated length of the heater).

Figure 19. Check-out Test 2 during disassembly.

Preparations for tests with prototypic corium material are underway at INEEL. As noted above, the simulated core catcher for these tests will be thermally sprayed with an Inconel 718 bond coating beneath a ZrO_2 insulator coating. It is anticipated that this coating will delay, if not prevent, the heatup and failure of the simulated core catcher.

IV. CONCLUSIONS

A joint U.S.-Korean effort is underway to design and evaluate the feasibility of an enhanced in-vessel core catcher . To reduce cost and simplify manufacture and installation, this new core catcher design consists of several interlocking sections that are machined to fit together when inserted into the lower head. Each section of the core catcher consists of two material layers with an option to add a third layer (if deemed necessary): a base material, which has the capability to support and contain the mass of core materials that may relocate during a severe accident; an insulator coating material on top of the base material, which resists interactions with high-temperature core materials; and an optional coating on the bottom side of the base material to prevent any potential oxidation of the base material during the lifetime of the reactor.

It should be noted that only preliminary core catcher design and evaluations will be completed in this INERI. If feasibility studies demonstrate that the proposed core catcher design and materials are viable and enhance the potential for IVR, more detailed studies and testing are needed before this concept is implemented in a reactor design. Such testing would confirm the long-term endurance of the proposed materials to hydrodynamic loads during operating and accident conditions. In addition, confirmatory testing of irradiation and coolant chemistry effects on coating performance may be warranted.

Results from scoping thermal and structural analyses suggest that an in-vessel core catcher is feasible and could offer significant protection to the vessel during a severe accident. Analyses results provide insights about the thickness and type of material that should be selected for each layer of the core catcher. In addition, analyses suggest that the proposed in-vessel core catcher will have negligible impact on coolant flow within the vessel.

Materials interaction tests provide additional insights about the core catcher design. At this time, scoping analyses and materials testing suggest that the core catcher base material should be stainless steel (SS 304). Evaluation efforts suggest that the insulator coating should be applied using thermal plasma spray techniques. Although several candidate coatings appear viable, materials interaction test results suggest that the insulator coating should consist of a 500 μm thick ZrO_2 coating over a 100 μm thick bond coating of Inconel 718.

Preparations are underway to evaluate the performance of proposed core catcher materials when exposed to prototypic corium materials. The designs of a test assembly and a unique heater for heating prototypic corium materials have been completed; and their performance has been demonstrated. As discussed in this paper, it is anticipated that the proposed test assembly and heater will be able to melt the corium so that the performance of proposed core catcher materials can be assessed during the last year of this research effort.

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